Measuring the plasma environment at Mercury:  
The fast imaging plasma spectrometer

P. L. KOEHN1*, T. H. ZURBUCHEN1, G. GLOECKLER1,2, R. A. LUNDGREN1 AND L. A. FISK1

1University of Michigan, Atmospheric, Oceanic and Space Sciences Department, Ann Arbor, Michigan 48109-2143, USA  
2University of Maryland, Physics Department, Space Research Group, College Park, Maryland 20742, USA  
*Correspondence author’s e-mail address: koehn@umich.edu

(Received 2002 January 25; accepted in revised form 2002 May 13)  

Abstract—The plasma environment at Mercury is a rich laboratory for studying the interaction of the solar wind with a planet. Three primary populations of ions exist at Mercury: solar wind, magnetospheric, and pickup ions. These pickup ions are generated through the ionization of Mercury's exosphere or are sputtered particles from the Mercury surface. A comprehensive mission to Mercury, such as MESSENGER (MErcury: Surface, Space ENvironment, GEnochemistry, Ranging), should include a sensor that is able to determine the dynamical properties and composition of all these plasma components. An instrument to measure the composition of these ion populations and their three-dimensional velocity distribution functions must be lightweight, fast, and have a very large field of view.

The fast imaging plasma spectrometer (FIPS) is an imaging mass spectrometer, part of NASA's MESSENGER mission, the first Mercury orbiter. This versatile instrument has a very small footprint, and has a mass that is ~1 order of magnitude less than other comparable systems. It maintains a nearly full-hemisphere field of view, suitable for either spinning or three-axis-stabilized platforms. The major piece of innovation to enable this sensor is a new deflection system geometry that enables a large instantaneous (~1.5σ) field of view. This novel electrostatic analyzer system is then combined with a position sensitive time-of-flight system. We discuss the design and prototype tests of the FIPS deflection system and show how this system is expected to address one key problem in Mercury science, that of the nature of the radar-bright regions at the Hermean poles.

INTRODUCTION

In 2004, the MESSENGER (MErcury: Surface, Space ENvironment, GEnochemistry, Ranging) spacecraft will be launched on its journey to Mercury. It will be our first visit since the 1970s to this planet. This is a highly constrained mission in terms of mass and power, and much effort is going into minimizing the necessary resources used, while maximizing the science output (Solomon et al., 2001; Gold et al., 2001).

The plasma environment at Mercury is a rich laboratory for the study of space physics. The solar wind measurements between 0.3 and 1.0 AU were performed by the Helios 1 and 2 spacecraft (e.g., Schwenn, 1990, and references therein). All Mercury ion measurements are exploratory; there are no ion measurements from the Mariner spacecraft (Ogilvie, 1974), and the constraints from remote sensing measurements are not strong. Based on the measured Mercury dipole moment and the heliospheric environment, three-dimensional numerical simulations have been constructed to predict and examine the Hermean plasma environment. These simulations show that the planet is expected to have a magnetosphere similar to Earth in configuration (Fig. 1), but with a tenuous atmosphere and ionosphere (Russell et al., 1988; Killen and Ip, 1999; Kabin et al., 2000).

Mercury's magnetosphere, therefore, provides a unique opportunity to study the interaction of the solar wind with a planet that is very different from the Earth. Pickup ions are of particular interest, as they allow an orbiting instrument to directly measure particles from the crust of the planet. While photoionization is the primary mechanism for pickup ion production, solar wind sputtering is also a possibility. Due to the smaller scale of the magnetosphere, solar wind or energetic particles are able to strike the surface of Mercury, particularly during high or variable interplanetary magnetic field (IMF) time periods (Luhmann et al., 1998; Killen et al., 2001). Under certain unusual solar wind conditions, the solar wind dynamic pressure is large enough that it can overwhelm and compress the Mercury magnetic field to the planetary surface (Kabin et
al., 2000; Hood and Schubert, 1976). In this case, the bulk solar wind impacts the Hermean surface and sputtering intensifies, possibly leading to a very variable plasma population. Under any of these circumstances, pickup ions can be formed from exospheric neutrals by photoionization, electron impact, or charge exchange with solar wind ions (Goldstein et al., 1981; Potter and Morgan, 1986). After ionization, these particles gyrate around the planetary or heliospheric magnetic field to form a pickup ion population (e.g., Ip, 1986). These pickup ions are further energized by this interaction with the magnetic field, or by wave–particle interactions or reconnection events (e.g., Eraker and Simpson, 1986) further from the planet. Measuring the composition of these pickup ions leads to direct sampling of the composition of Mercury. It is therefore an important part of measurements that lead to a better understanding of the planet’s history and the processes that shape the surface of the planet.

In addition to the pickup ions, particle populations of solar wind and atmospheric ions found in the magnetosphere are also part of the plasma environment. These populations, as estimated from the references given above and Bida et al. (2000) are detailed in Table 1. Upstream of the magnetopause, the solar wind density is ∼60 cm−3 with a velocity of 400 km s−1, while just inside the nose of the magnetopause the density increases to 210 cm−3 with a velocity of 154 km s−1 (data from Kabin et al., 2000). It is clear from these values and Table 1 that a successful plasma instrument will require a large dynamic range in order to detect all three populations. It must also have a high time resolution to detect rapid changes in the distributions of magnetospheric and pickup ions. Since MESSENGER is a three-axis stabilized spacecraft, a wide field of view is also necessary. The instrument should also be lightweight, use very little power, and have a small footprint.

We will first provide an overall description of the fast imaging plasma spectrometer (FIPS) and then focus on the newly developed electrostatic analyzer (ESA), which enables this low-mass instrument. First, extensive ion simulations are discussed. We then compare these simulations with measurements from a 1:1 prototype. We show how this electrostatic analyzer system is used to address a key problem in Mercury science. We estimate the surface densities of OH+ and S+ and calculate the resulting count rates in the FIPS.
TABLE 1. Three populations of ions expected in the Mercury plasma environment.

<table>
<thead>
<tr>
<th>Population</th>
<th>Composition</th>
<th>E/Q range (keV/e)</th>
<th>Fluxes (cm(^{-2}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar wind</td>
<td>H(^+), He(^{2+}), O(^{6+}) to O(^{8+}), etc.</td>
<td>0.2–10</td>
<td>3 \times 10(^9)</td>
</tr>
<tr>
<td>Magnetospheric</td>
<td>H(^+), He(^+), He(^{2+}), O(^{6+}) to O(^{8+}), O(^+), etc.</td>
<td>0.2–15</td>
<td>10(^7) to 5 \times 10(^9)</td>
</tr>
<tr>
<td>Pickup</td>
<td>H(^+), (^3)He(^+), (^4)He(^+), C(^+), N(^+), O(^+), Ne(^+), Na(^+), Si(^+), S(^+), K(^+), Ar(^+), Ca(^+)</td>
<td>0.05–150</td>
<td>&lt;10(^5) cm(^{-2}) s(^{-1}), but highly variable</td>
</tr>
</tbody>
</table>

Instrument to determine whether the radar-bright polar regions of Mercury are due to cold-trapped deposits of water or sulfur.

**FAST IMAGING PLASMA SPECTROMETER OVERVIEW**

The FIPS ESA was first described by Zurbuchen et al. (1998). It was a simple cylindrical mirror system with a perforated entrance dome and an array of field control rings. These rings maintained a uniform field between the outer and inner electrodes. A number of modifications have been made since then, but the basic principles of operation have remained the same, as illustrated in Fig. 2.

Particles with velocity \( V \), mass \( m \) and charge \( q \) enter the sensor through the aperture, which allows a near-hemispherical access to FIPS. The deflection system selects ions with a given energy per charge

\[
\frac{E}{q} = \frac{1}{2}\frac{mV^2}{q} \tag{1}
\]

The \( E/q \) range is selected by adjusting the FIPS deflection voltage, typically stepping from the highest \( E/q \) of 20 keV/e to the lowest \( E/q \) of 20 eV/e. The penetrating particles are then post-accelerated by 15 kV and enter a linear time-of-flight telescope. The "stop" signal from this telescope is derived from secondary electrons that are emitted from a very thin (~1 \( \mu \text{g/cm}^2 \)) carbon foil. These secondary electrons are reflected onto a position-sensitive multi-channel-plate (MCP) assembly. The position derived from this process determines the velocity direction \( V/W \). The "stop" signal is determined from a second MCP assembly that detects the ion. The "start" and "stop" signals define the time-of-flight \( t \). This time-of-flight, \( E/q \) and the position information then determine \( V \) and mass per charge \( m/q \) (Zurbuchen et al., 1998). A similar principle of operation was used in conjunction with a solid-state detector (SSD) as an independent energy measurement, allowing the additional calculation of the particle's mass (Gloeckler and Hsieh, 1979; Gloeckler, 1990). Due to mass and power constraints, the FIPS

---

**FIG. 2.** Block schematic of the FIPS electrostatic analyzer (ESA) and time-of-flight (TOF) telescope. Measurements of \( E/Q \) via the electrode voltage and time-of-flight telescope allow the determination of the transmitted particle's M/Q.
instrument has no SSD, and so only measured the incident particle's mass per charge.

There are two major differences between the FIPS ESA and the instrument described by Zurbuchen et al. (1998). First, the geometry of the electrostatic analyzer has been changed to a hybrid cylindrical mirror/curved plate analyzer geometry. Hemispherical plates replace the outer cylindrical electrode, eliminating the need for field support rings while still providing excellent ultraviolet photon rejection. Twin sets of logarithmically spaced collimators have been added, enhancing the ultraviolet rejection and reducing the analyzer's energy acceptance and increasing its energy and angular resolution. Field-free regions have also been added to the central (ground) electrode, further increasing the energy resolution and reducing the angular dependence of the analyzer constant.

The other major change since the previous description is the post-acceleration voltage. It has been increased from 5 to 15 kV in order to decrease the energy losses and angular scattering of heavy, singly charged pickup ions trajectories through the carbon foil, increasing the mass-range of the FIPS instrument. These effects were studied in a set of simulations using the software package SRIM2000 (Ziegler, 2001). We found that a higher post-acceleration voltage reduced uncertainties in time-of-flight and ion trajectories such that the mass per charge resolution for the system became dominantly a function of the energy per charge resolution of the ESA. FIPS's mass resolution ($m/\Delta m$) of 25 is comparable with other mass spectrometers in flight.

The FIPS ESA is a completely new instrument design, significantly different from other instruments currently in use. The plasma experiment for planetary exploration (PEPE) (D. T. Young, pers. comm., 2001) from Deep Space 1 and the Cassini plasma spectrometer (CAPS) (D. T. Young, pers. comm., 2001) from the Cassini mission are two examples of tophat analyzers, a very popular narrow electrode gap energy analyzer. Both of these tophat-shaped instruments have a small instantaneous field of view—only a few degrees in elevation, but a wide range (160–360°) in azimuth. CAPS is mounted to a scan platform, which rotates in order to increase the instrument's total field of view, while PEPE utilizes scanning electric fields to draw particles into the analyzer, increasing its field of view to more than 2σ steradian by scanning this deflecting voltage, therefore increasing the instrument's duty cycle. FIPS has a nearly hemispherical instantaneous field of view as a result of its geometry, and requires no additional fields or platforms. The tophat design's high analyzer constant (typically ~10) allows the entrance system to bend the trajectories of higher energy particles and allow them to be transmitted through the system using a lower electrode voltage. This provides a much higher energy range than what is inherent in the FIPS design, representing a tradeoff between a large field of view and a wide energy range. The solar wind ion composition spectrometer (SWICS) from ACE (Gloeckler et al., 1998) is another comparable system. SWICS is a curved-plate analyzer with a small instantaneous field of view, increased to more than 2σ sr by the spinning spacecraft. It also has a high analyzer constant, giving it an energy range that is much higher than FIPS. For a three-axis stabilized spacecraft, the 1.5σ sr instantaneous field of view and low mass of FIPS are a good trade for a low analyzer constant.

The innovative design of the FIPS ESA started with a conceptual design for a small solar wind composition spectrometer described in a proposal to NASA for the solar probe mission in situ instruments package (Gloeckler, pers. comm., 1994) followed by a fuller description of the instrument and calculations of its response (Zurbuchen et al., 1998). The current FIPS ESA was developed from that idea through a number of simulation iterations, and we now have constructed a working prototype. This adjusted design is simpler in many ways, as will be discussed in the next section. The next section will discuss the detailed simulation of the final FIPS ESA design, and present ion-optical tests of a flight-like prototype system.

**ELECTROSTATIC ANALYZER SIMULATION**

We have performed fully three-dimensional simulations of the prototype electrostatic analyzer using Simlon, a ray-tracing software package (Dahl, 2000). Simulations of FIPS have been configured to match the prototype's geometry. Figure 3 details this configuration and shows a few sample trajectories.

The goal of these simulations was to provide an estimate of the four important performance parameters of this instrument: energy resolution, analyzer constant, angular resolution, and effective aperture. In this series of simulations, we used an initial data set of $3 \times 10^6$ ions uniformly distributed in initial energy and incidence angle. These ions were launched from a cylindrical plane such that they completely illuminated one sector aperture of a simulated FIPS entrance system. The simulated geometry was of sufficient resolution to model all the important features of the entrance system. An ion-optical system of the FIPS ESA’s complexity requires a great deal of computing power to be accurately represented in a simulation environment, so efforts were made to utilize the ESA's symmetry wherever possible. The minimum resolution in the simulation was 5 gridpoints/mm. Transmitted ion trajectories are far enough from any electrode surface that they will be unaffected by any field irregularities introduced by this relatively low resolution. A large portion of the system was created by rotating a 10 gridpoints/mm two-dimensional frame around the central axis of symmetry, further decreasing the computer system requirements. A virtual ion traveling through this rotated frame will "see" a three-dimensional geometry and field, so this approximation is acceptable. The collimator plates are rendered at an even higher resolution (20 gridpoints/mm), and are used as beam stops within field-free regions of the simulation held at ground potential. The simulated collimator plate slits are more open than the collimators installed in the
Measuring the plasma environment at Mercury

Fig. 3. Simulation geometry of the FIPS ESA. The black lines are sample trajectories that show the mapping of entrance angle to radial distance from the center of the system.

prototype. This should result in a slightly shifted simulated \( \Delta E/E \) value than measured with the prototype. In addition, the finlike azimuthal collimators are not included in the simulation—particles with a large \( \phi \) component to their velocities are omitted. Each ion's initial and final energy, direction and position were stored for analysis, and the transmitted ion information was used to generate estimates of the instrument's performance characteristics. The left column in Table 2 summarizes these measurements.

The energy resolution for a given beam energy and incidence angle is found by measuring the width (full width at half-maximum (FWHM)) of the particle energy vs. counts profile generated from the simulation data. Figure 4 shows the overall angular and energy acceptance for the simulated instrument. Plots such as this demonstrate the total energy and angular response of an instrument to an isotropic plasma population, and allow developers to see in a single figure the energy resolution of the instrument as a function of angle, or the angular resolution as a function of particle energy. It is clear from the figure that energy resolution will be a slight function of incidence angle—as the incidence angle increases (gets further from the system symmetry axis), \( \Delta E/E \) should decrease. The energy resolution, averaged over all angles, is 4.2% (FWHM).

The analyzer constant for an instrument is used to convert a deflection voltage setting on the ESA into the energy per charge of a given transmitted particle. The simulated instrument has a fixed deflector voltage, so one must simply find the peak \( E/Q \) for a given angle transmitted by the system, and divide this value by the deflector voltage. As seen in Fig. 4, this is also a slight function of angle, but is still very flat overall. This flatness represents a significant change from the Zurbuchen et al. (1998) design, where the analyzer constant was strongly dependent on the particle angle of incidence. This is a major improvement in design, as measurements of energy spectra are now independent of time-of-flight and position measurements. This independence dramatically simplifies data analysis. A detailed analysis of simulation data produces a mean analyzer constant of 1.36.

Angular resolution is important in this instrument for two reasons. First, a high angular resolution will allow us to accurately measure the three-dimensional velocity distribution function of the solar wind, magnetospheric, and pickup ions. It is also important for a second, subtler reason. In this instrument, both the energy resolution and the analyzer constant are slight functions of angles (see Fig. 4). If we accurately know the angle at which a particle entered the system, we can

<table>
<thead>
<tr>
<th>Performance parameter</th>
<th>Simulation</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy resolution (%)</td>
<td>4.2</td>
<td>3.6</td>
</tr>
<tr>
<td>Analyzer constant</td>
<td>1.36</td>
<td>1.36</td>
</tr>
<tr>
<td>Angular acceptance (sr)</td>
<td>1.47( \pi )</td>
<td>1.47( \pi )</td>
</tr>
<tr>
<td>Angular resolution (°)</td>
<td>5.6</td>
<td>8.5</td>
</tr>
<tr>
<td>Effective aperture (mm²)</td>
<td>0.055</td>
<td>0.094</td>
</tr>
</tbody>
</table>
determine to better accuracy that particle's energy per charge, and hence its mass per charge.

For the simulations, we calculated the population density of transmitted ions in the plane of the carbon foil of the system and measured the width (FWHM) of the profile of radial position. For this system, the radial position of the ion at the carbon foil is directly mappable to its angle of incidence at the entrance aperture, so the width of the radial position profile is a measure of the angular resolution of the system. Using this method, the simulation predicts a 5.6° mean angular resolution (FWHM) for the instrument, with slight variations with angle.

The effective aperture is a measure of the total geometric acceptance of a system, including aperture size and beam attenuation effects. This parameter is measured by illuminating the system (simulated or otherwise) aperture with a very cold beam of known flux per area, and measuring the peak transmitted flux at the system exit. The effective aperture is then calculated as the ratio of the incident and transmitted flux. Simulations give a mean effective aperture of 0.055 mm²/pixel, with slight variation with angle. This value for the effective aperture translates directly to a relatively low particle transmission rate that is necessary in the Mercury magnetosphere, since the FIPS time-of-flight electronics can only accept count rates <100 kHz. Opening up the entrance aperture, or the collimator slits, or some combination of both will increase this effective aperture, allowing the instrument to be used in any space plasma environment.

Simulations of the ESA portion of FIPS show it to be of sufficient resolution and sensitivity to achieve the plasma science goals for the MESSENGER mission. The next step was to construct a prototype that matched the simulated system, and characterize it.

### Prototype Electrostatic Analyzer Measurements

Once the FIPS ESA prototype was constructed, a testing program was developed that would both prove that the system would work, and verify that our simulations were accurate. The simulations used ions of random velocity and angle, effectively tracing out every possible trajectory through the instrument. To verify these simulations, then, it was necessary that a beam of ions should be flown through at all possible angles, and at several energies.
The FIPS ESA prototype was mounted in a vacuum chamber at the Goddard Space Flight Center Beam Facility on a stage with two translational degrees of freedom and two rotational degrees of freedom. A proton beam could then be passed into the prototype at any angle within the instrument's field of view. As the ESA only measures energy per charge, this proton beam was adequate. To accurately measure the angular resolution of the instrument, the exit positions of the transmitted ions must be detected. To this end, we employed a position-sensing MCP system manufactured by Quantar Technology. Two MCPs amplify each ion impact, and a resistive anode mounted at the rear of the system detects the centroid of the resulting electron cloud. This Quantar device is mounted at the rear of the prototype, in the plane of the carbon foil. Figure 5 summarizes the experimental setup, and includes a photograph of the prototype entrance system.

Four proton beams of fixed energy were used: 500 eV, and 2, 5, and 10 keV. This covers nearly the entire FIPS energy range. The beam energy was held constant, and the ESA deflection voltage was swept through its full range. The Quantar, in integration mode, recorded the number or protons impacting the MCP per second for each voltage step. Peaks or other interesting features of the resulting profiles were then imaged using the Quantar's imaging mode. These measurements were then repeated for the entire range of elevation angles (15–78°) within the prototype's field of view, in 1° increments. The cylindrical symmetry of the ESA allows this series of measurements to completely characterize the prototype; however, for completeness, measurements were recorded at other azimuthal angles as well.

As the goal of the measurement series was to validate the simulations, the same four parameters were calculated for the measured data as were done for the simulated data (see Table 2). Energy resolution was calculated by measuring the width of the voltage step vs. counts profile for each beam angle. Figure 6 shows a comparison of the simulated and measured profiles for elevation angles of 22 and 63°. Note the side lobe on the 63° profile. This is due to an interference pattern that exists as a result of our double collimator design. The collimator design is currently being re-examined. The shift in energy between the 63° simulation and measurement results is due to a very small disagreement between the model inner electrode radius and the prototype. The simulation geometry is being updated. For a 10 kV beam, the mean energy resolution is 3.6% (FWHM), with some small variation with angle. The analyzer constant for the system was calculated by dividing the beam energy by the voltage step for each angle, just as was done in the simulations. The mean analyzer constant is 1.36, also exhibiting a slight variation with beam angle. A mean effective aperture of 0.094 mm² was found by dividing the transmitted count rate of the prototype by the known incident flux, as was done for the simulations. Finally, an image of the particle impact distribution in the plane of the carbon foil at the peak beam transmission for each incidence angle is taken using the imaging mode of the Quantar position sensing MCP. The FWHM radial width of this distribution is measured and taken to be the angular resolution for that particular angle. The prototype data reveals a mean resolution of 8.5°. As with the analyzer constant and energy resolution, the angular resolution and effective aperture vary slightly with angle.
Table 2 summarizes these results, and compares them to the simulation results. Subtle differences between the simulation and the constructed prototype exist, and are primarily responsible for the energy and angular resolution differences. The simulation is being updated to accurately reflect the installed near-flight-version azimuthal collimators and collimator plates. In addition, all collimators will be re-rendered at a higher resolution. These modifications should bring the prototype and simulation data sets even closer together. The differences in the effective aperture are due to imperfections in the entrance aperture of the system, which will naturally not exist in the flight version of the instrument. Some modification to the prototype is also expected, to further suppress any angular dependence of the analyzer constant, effective area, and energy and angular resolution. Once the flight version of the FIPS instrument is constructed, it will be calibrated using beams of heavy ions, rather than protons as was done for the prototype ESA.

**FAST IMAGING PLASMA SPECTROMETER SIMULATIONS FOR MERCURY MAGNETOSPHERE**

The FIPS ESA has been simulated and a prototype has been constructed, and we have shown that the instrument works as expected. Now we apply the performance characteristics that we have measured to a simulated Mercury plasma environment. This section details this study and demonstrates that the FIPS instrument is well suited to Hermean science.

The typical orbit of the MESSENGER spacecraft around Mercury is highly elliptical (see Fig. 1), and precesses very little in a non-rotating reference frame (Solomon et al., 2001), changing its position relative to the Sun–Mercury line. Once the spacecraft is in orbit around Mercury, the FIPS instrument will experience a wide variety of plasma conditions and ion populations within each orbit and throughout the mission. The instrument's sensitivity must be such that it is neither overwhelmed by particles nor unable to detect anything.
With this in mind, we have constructed a model based on the FIPS performance parameters from the previous section. It will, for any given point in the magnetosphere, predict the proton count rate from the instrument as a function of the E/Q of the transmitted particles. In addition, it will produce images of particle spatial distributions in the plane of the FIPS carbon foil.

For this simulation, the magnetospheric data was taken from Kabin's magnetohydrodynamic (MHD) simulation of Mercury (Kabin et al., 2000). This model solves the MHD equations for the interaction of the solar wind plasma with a planetary magnetic field. It provides bulk flow velocities, plasma temperatures and magnetic field vectors for any given point in the system. As an example, we here look at the FIPS performance while near the nose of the magnetopause, as shown in Fig. 1. The plasma has a high density (210 cm$^{-3}$), but low thermal and bulk speeds (~120 km s$^{-1}$). Here we would expect to see primarily shocked solar wind plasma as it builds up and flows around the planetary body. FIPS's 64 s normal scan mode, or its 2 s "burst scan mode" gives it the ability to quickly reconstruct the three-dimensional plasma velocity distribution which will be invaluable for studying this phenomenon.

Figure 7 shows the predicted counts per ESA voltage step, or equivalently, the measured particle populations E/Q, as well as the distribution of transmitted particle impact points on the carbon foil for a maxwellian distribution of particles matching the above parameters. With a peak count rate of >40 kHz, the reconstruction of the particle velocity vectors from the position information shown can be accomplished quickly in either mode, allowing us to detect rapid changes in this region of the magnetosphere. Electronic constraints limit the FIPS maximum count rate to ~100 kHz, which we are well below, even in the region between the tail and the edges of the bow shock.

This simulation shows that the FIPS ESA will image the velocity distribution function of ambient plasma. It should be noted that for this model the input plasma distribution is maxwellian, and it is likely that velocity distribution function in the Mercury environment may not be thermalized. As the FIPS instrument builds its image of the distribution function one ion event at a time, it will measure the nature of any distribution function regardless of state. This event-by-event measuring capability adds to its flexibility and appropriateness for Mercury science.

**MERCURY SCIENCE: RADAR-BRIGHT REGIONS OF THE HERMEAN SURFACE**

Although Mercury has been studied for decades, unanswered questions and mysteries abound. The MESSENGER spacecraft and its payload of instruments will answer a number of these questions, and undoubtedly raise new ones. One major question of recent discovery is the nature of the radar-bright regions near the poles of Mercury. In this section we show how the FIPS instrument will address this problem through the detection of OH or S pickup ions.

These radar-bright regions have been reported by Slade et al. (1992) and Harmon and Slade (1992), and were concluded to be the result of volatiles, particularly water, trapped in permanently shadowed craters near the poles (Slade et al., 1992; Harmon and Slade, 1992; Butler et al., 1993; Harmon et al., 1994). Killen et al. (1997) calculates the column abundance of a hydroxyl (OH) exosphere as a result of trapped water ice. Hodges (2002) argues that water would not be transported to the lunar poles as readily as previously thought, and that it is unlikely or impossible that water has been cold-trapped in lunar craters. The same argument can be used for Mercury. However, this argument does not rule out the possibility of cometary delivery of water to the permanently shaded regions. Sprague et al. (1995) proposes that the radar-bright regions are cold-trapped deposits of elemental sulfur, rather than water, and estimates the column abundance of sulfur by scaling Na column abundances, assuming that the creation and loss processes for atmospheric Na and S are similar.

In either scenario, OH or S neutrals are liberated from the planetary surface by sputtering, photodesorption, meteoric impact or other processes. As seen in Table 3, both OH and S have relatively long ionization lifetimes, and will travel in ballistic "hops", first thermalizing to the surface temperature, and eventually ionizing. They will be accelerated by the

<table>
<thead>
<tr>
<th>Value*</th>
<th>OH$^+$</th>
<th>S$^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column abundance (cm$^{-2}$)</td>
<td>$1.3 \times 10^{11}$</td>
<td>$2.4 \times 10^{12}$</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>Scale height (km)</td>
<td>36</td>
<td>19</td>
</tr>
<tr>
<td>$V_{\text{source}}$ (m s$^{-1}$)</td>
<td>513</td>
<td>374</td>
</tr>
<tr>
<td>$t_{\text{ballistic}}$ (s)</td>
<td>196</td>
<td>143</td>
</tr>
<tr>
<td>0.31 AU ionization rate (quiet/active Sun s$^{-1}$)</td>
<td>$1.1/2.5 \times 10^{-5}$</td>
<td>$2.5/6.7 \times 10^{-6}$</td>
</tr>
<tr>
<td>0.31 AU ionization lifetime (quiet/active Sun h)</td>
<td>111/41</td>
<td>25/11</td>
</tr>
<tr>
<td>Surface ion density (quiet/active Sun average cm$^{-3}$)</td>
<td>33</td>
<td>3347</td>
</tr>
<tr>
<td>Pickup thermal velocity (km s$^{-1}$)</td>
<td>114</td>
<td>84.7</td>
</tr>
<tr>
<td>Pickup most probable velocity (km s$^{-1}$)</td>
<td>124</td>
<td>117</td>
</tr>
</tbody>
</table>

*Sources for values are listed in the text.
Fig. 7. Simulation of counts per energy step for the FIPS instrument when MESSENGER is near the subsolar point in its orbit. Panel (a) shows the count rate for a full voltage sweep of the FIPS instrument, with a peak rate of $5 \times 10^4$ counts/s. Panel (b) is an image in radius and azimuthal angle of the distribution of particles impacting the carbon foil for the peak voltage step. The cropped distribution is due to the beam entering the entrance system at the edge of its field of view.
motional electric field of the solar wind, which maps down to
the surface of Mercury due to the open nature of the Hermean
magnetosphere (Kabin et al., 2000). These ions have very large
gyroradii, of order a quarter of the planetary radius. They therefore
travel through the magnetosphere with a very complex trajectory,
and are either swept away from the planet, or accelerated back
toward the planet's surface, where they are implanted or neutralized
and eventually re-emitted (Hunten et al., 1988).

Once ionized, the pickup ions are rapidly accelerated to
high energies, beyond the 20 keV per charge limit of the FIPS
ESA. Ions of higher energy will be detected by the energetic
plasma spectrometer (EPS) instrument on the MESSENGER
spacecraft (Gold et al., 2001). Relatively close to the planet
surface, however, they should be within the FIPS energy range.
The MESSENGER orbit brings the spacecraft to a minimum
altitude of 250 km, near the north pole of Mercury, so neutrals
ionized near the surface in this polar region have the highest
likelihood of being detected. We now use the same model as
described in the previous section to estimate the FIPS count
rates for OH \(^+\) and S \(^+\) from the MESSENGER periapsis altitude
of 250 km.

We will use the following approach to calculate the FIPS
count rate for each species. First, we calculate the neutral
surface density of OH and S. These neutrals travel through the
Mercury exosphere in ballistic hops, so we calculate the
time of flight for these hops and use this as the neutral's
residence time in the exosphere, the time in which the neutral
can be ionized. We then apply this flight time to the ion
production rate to calculate the surface ion density. These ions
are then accelerated by the solar wind motional electric field
away from the planet, where they are detected by the FIPS.
Finally, we calculate the pickup ion bulk and thermal velocities
at 250 km from the surface, and then fold the resulting ion
fluxes through our simulated instrument to generate count rates.

Neutral Surface Density

Sprague et al. (1995) estimates the neutral sulfur column
density to be \(2.4 \times 10^{12} \text{ cm}^{-2}\) by scaling the neutral sodium
column abundance. There is some uncertainty associated with
this number, as it assumes the creation and loss rates of sulfur
to be similar to that of sodium. Killen et al. (1997) calculates
the OH column density to be \(1.3 \times 10^{11} \text{ cm}^{-2}\), based on
calculations of the water abundance and photolysis rates. For
an average temperature of 270 K, based on Fig. 4 from Smith
et al. (1978), which in turn was derived from Chasse et al.
(1976), the OH and S scale heights are 36 and 19 km,
respectively. Dividing the column abundance of a species by
its scale height at the surface gives us an estimate of the surface
density of the species. The hydroxyl and sulfur surface
densities are then \(3.6 \times 10^{4} \text{ cm}^{-3}\) and \(1.3 \times 10^{6} \text{ cm}^{-3}\),
respectively. The sulfur density calculated here is higher than
that estimated by Sprague et al. (1995) because of the lower
temperature used in the scale height calculation.

Ionization Rate and Residence Time

Huebner et al. (1992) provides ionization rates at 1 AU for
both quiet and active Sun conditions. For sulfur, the quiet Sun
ionization rate is \(1.1 \times 10^{-6} \text{ s}^{-1}\), and \(2.4 \times 10^{-6} \text{ s}^{-1}\) for an active
Sun. As OH is more likely to be photodissociated into O and H,
the OH ionization rate is smaller, with values of \(2.4 \times 10^{-7} \text{ s}^{-1}\)
and \(6.4 \times 10^{-7} \text{ s}^{-1}\), for quiet and active Sun conditions. These
must be scaled with the inverse square of Mercury's orbital
distance from the Sun (0.31 AU). After scaling, we see that
the ionization lifetime for sulfur during quiet (active) solar
conditions is 25 (11) h, much shorter than the 111 (41) h
ionization lifetime for neutral OH. From these relatively long
ionization lifetimes we can infer that the neutrals will bounce
a number of times and be thermalized before ionizing. Neutrals
will leave the surface with a velocity \(V_{\text{bounce}}\) corresponding
to their temperatures, at an average angle of 45° to the surface.
They will then have a ballistic flight time of (Hunten et al.,
1988):

\[
\tau_{\text{ballistic}} = \sqrt{2 \frac{V_{\text{bounce}}}{g}} \text{ s}
\]  

(2)

By Eq. (2), S and OH neutrals have average flight times of 143
and 196 s, respectively, using a Mercury surface gravity of
3.7 m s\(^{-2}\).

Ion Surface Density

In order to estimate an upper limit of the ion abundances,
we will assume that all neutrals ionized within one scale height
of the surface will be swept upward by the solar wind motional
electric field and through the region surrounding the spacecraft.
The ion density at 1.1 \(R_{\text{M}}\) (250 km) can then be approximated
by the ion density within the first scale height. Extending the
method in Killen et al. (1997), the ion density at the surface
can be calculated from:

\[
[X^+ \text{ cm}^{-2}] = [X] \tau_{\text{ballistic}}
\]  

(3)

where \([X^+]\) is the ion density, \([X]\) is the neutral surface
density, \(R\) is the scaled ionization rate, and \(\tau_{\text{ballistic}}\) is the
ballistic flight time of the thermalized neutral, the time
during which ionization can take place. By Eq. (3), the
surface densities of S \(^+\) and OH \(^+\) are 3347 and 33 cm\(^{-3}\),
respectively, using average values between quiet and active
solar conditions.

Ion Velocities

In order to estimate the pickup ion velocities at 250 km
altitude, we have constructed a model that produces ion
trajectories in a static magnetosphere. The ion gyroradii are
very large, and move through a complex magnetic field. A
fluid model calculation is inadequate to accurately produce
ion trajectories in such a scenario; therefore, we solve for each ion the equations of motion:

\[
\begin{align*}
\frac{d\vec{x}}{dt} &= \vec{\dot{v}} \\
\frac{d\vec{v}}{dt} &= \frac{q}{m} \left( \vec{\dot{v}} \times \vec{B} - \vec{u} \times \vec{B} \right) + \frac{\vec{g}}{m}
\end{align*}
\] (4)

Here, \(\vec{v}\) is the particle velocity vector; \(m\) and \(q\) are the ion mass and charge, respectively; \(\vec{u}\) is the plasma bulk velocity vector; \(\vec{g}\) is the gravitational force of the planet; and \(\vec{B}\) is the local magnetic field vector. The \(\vec{u} \times \vec{B}\) motional electric field accelerates the ions through the magnetopause and into the solar wind stream.

Rather than a simple dipolar magnetic field, this model uses the simulated Hermean magnetosphere from Kabin et al. (2000) as input. This model is the most accurate to date, generating a magnetospheric configuration consistent with the interaction of a Parker spiral solar wind with the insulating body of Mercury and its intrinsic magnetic field. Figure 8 shows the trajectories of 720 OH\(^+\) ions, each leaving the north polar surface with a velocity corresponding to the surface temperature. Pickup ions will also be found leaving the south pole of the planet, but the MESSENGER spacecraft periapsis is near the north pole, as seen in Fig. 1, so only pickup ions of north polar origin are considered in this study.

At each point along the trajectory, the ion's energy is recorded. Figure 9 shows the distribution of OH\(^+\) energies at increasing radial distances from the surface of Mercury. From this figure it is clear that most of the ions are well within the 20 keV per charge limit of the FIPS. The distribution for S\(^+\) is similar. From this calculation, the most probable velocities for OH\(^+\) and S\(^+\) are 124 and 117 km s\(^{-1}\), respectively. We will use these velocities as the bulk plasma velocity in our count rate calculation. After ionization, the newly born pickup ions eventually take on a thermal velocity equal to the solar wind speed. However, at 250 km, the ions are not fully accelerated, but have an energy distribution as is shown in Fig. 9 (\(R = 1.1R_m\)). We will then take the thermal velocity to be the width of this energy distribution.

**Fast Imaging Plasma Spectrometer Count Rates**

With the calculated ion densities, and the thermal and most probable velocities from the model, we can estimate the count rate detected by the FIPS instrument by integrating the particle distribution over the instrument's angular and energy ranges, including performance parameters discussed in the previous sections. Figures 10 and 11 show these estimated count rates as a function of analyzer voltage, and the particle distributions at the plane of the carbon foil within the instrument. For OH\(^+\), the peak count rate is \(6.0 \times 10^3\) counts/s, and for S\(^+\) the rate is \(5.6 \times 10^5\) counts/s. The S\(^+\) rate is large, and may be larger still.

**Fig. 8.** Simulated trajectories of north polar OH\(^+\) ions in a nominal Hermean magnetosphere. Ions are swept from the planet by the solar wind motional electric field. Trajectories for sulfur ions are similar, except for a larger gyroradius.
Fig. 9. Energy distribution of hydroxyl ions with increasing distance from the planet, up to 1.11 $R_m$. As expected, mean ion energy increases with increasing altitude. Note that the ion energies are well below the 20 keV limit of the FIPS ESA. Sulfur energy distribution is similar.
Fig. 10. Simulation of OH$^+$ counts per energy step for the FIPS instrument when MESSENGER is at the periapsis altitude of 250 km. Panel (a) shows the count rate for a full voltage sweep of the FIPS instrument, with a peak rate of $6.0 \times 10^3$ counts/s. Panel (b) is an image in radius and azimuthal angle of the distribution of particles impacting the carbon foil for the peak voltage step.
FIG. 11. Simulation of $S^+$ counts per energy step for the FIPS instrument when MESSENGER is at the periapsis altitude of 250 km. Panel (a) shows the count rate for a full voltage sweep of the FIPS instrument, with a peak rate of $5.6 \times 10^5$ counts/s. Panel (b) is an image in radius and azimuthal angle of the distribution of particles impacting the carbon foil for the peak voltage step.
based on a factor of 10 increase in the neutral sulfur column abundance in an erratum to Sprague et al. (1995). Table 3 summarizes the factors used in these calculations.

As we have shown, the FIPS instrument will detect measurable quantities of either OH$^+$ or S$^+$ (or both), and by doing so will address the physical nature of the polar anomalies. This measurement will therefore provide important constraints on the origin and evolution of the radar-bright polar deposits on Mercury.

SUMMARY AND CONCLUSIONS

We have shown that the FIPS satisfies the stringent requirements for making plasma measurements in the Mercury environment. Its energy and angular resolutions are sufficient to detect all three ion populations expected at Mercury. Its effective aperture is small enough to avoid the saturation of the MCP and electronics, and large enough to allow the reconstruction of three-dimensional velocity distributions within its 64 s scan period, or 2 s burst scan period. Proton detection times are being produced which will allow the detection of heavier species in the presence of the undoubtedly large solar wind proton flux. The FIPS's high mass resolution will allow the separation of all ionic species of interest, including carbon, nitrogen, oxygen and heavier species. These successfully predicted and tested operational parameters (in addition to FIPS' low mass, footprint, and power requirements) make this instrument the ideal solution for measuring the plasma environment at Mercury, and making important contributions to Mercury science. It is important to note, however, that the FIPS instrument is part of a larger spacecraft with a number of experiments on board. Measurements of higher energy ions by the EPS instrument (Gold et al., 2001), as well as magnetic field measurements by the magnetometer (MAG) instrument (Gold et al., 2001) will complement the FIPS measurements, allowing the study of the plasma environment with a level of detail not possible in the past.

Acknowledgements—The authors would like to thank the NASA Graduate Student Researchers Program, the Goddard Spaceflight Center, and Dr. Tom Moore of GSFC for their financial support for the measurement intensive. P. L. K. acknowledges Dr. Dennis Chorney (GSFC) for access to a beam facility and invaluable assistance; Floyd Hunsaker (GSFC), Jon Harvey (UM) and Chuck Navarre (UM) for mechanical, CAD drawing, and figure help; Kevin Sylves (UM) for assistance with measurement and simulation efforts; Frank Cray and Judy Furman (UM) for interesting discussions of the CAPS and PEPE instruments; and Eric Wilson, Christiane Jablonowski and Ben Lynch (UM) for atmospheric chemistry discussions. Special thanks go to the Lunar and Planetary Institute and their associates for travel support for the Mercury 2001 Conference in Chicago, Illinois. FIPS is supported by grant number 845762 from the Applied Physics Laboratory, NASA Prime Contract number NAS5-97271.

Editorial handling: P. Cassen

REFERENCES


